Drainage Capillary Pressure Curves in Arbuckle

By Mina Fazelalavi
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The Pc curves were derived based on a theoretical method (M.F.Alavi) that relates endpoints of capillary pressure curves to Reservoir Quality Index (RQI). Based on this investigation, there are good correlations between endpoints of capillary pressure curves (entry pressure and irreducible water saturation) and RQI.

The key well (well 1-32) was used to calculate Pc curves for the Arbuckle. Generated Pc curves from the NMR log of well 1-32 were used to find correlations between endpoints and RQI for determination of Pc curves. Pc curves from NMR were in mercury-air system and then converted to a CO_2-brine system (Fig. 1).

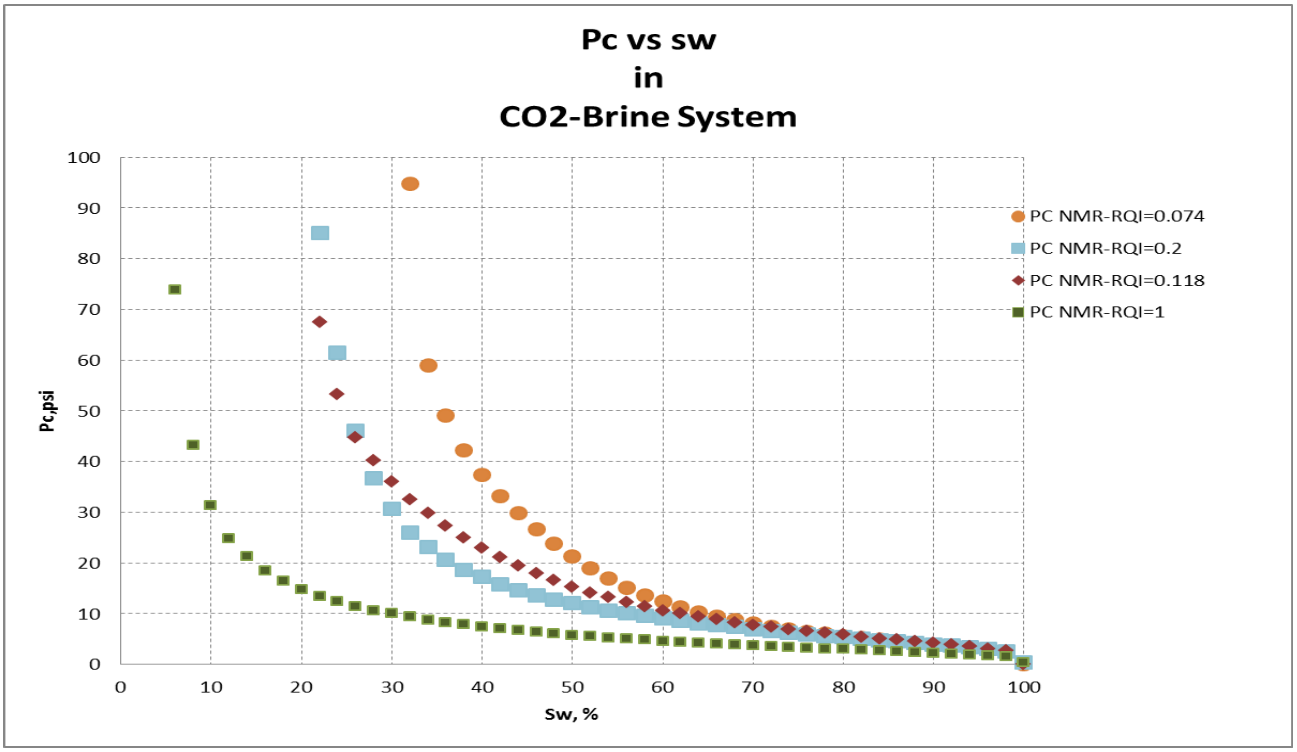


Figure 1: Pc curves generated from NMR

a. Entry Pressure

Based on SCAL data of other fields, a good correlation can be found between capillary entry pressure and RQI. Pore throat at entry pressure in well 1-32 was determined from Winland R35, and entry pressure was calculated from pore throat radius. Winland R35 was calculated using Equation 1:

$$\log R35 = 0.732 + 0.588 \log K - 0.864 \log \varphi \qquad \text{Eq. 1}$$

Previously, the permeability of the Arbuckle in Well 1-32 was determined. Based on porosity and the calculated permeability of Well 1-32, RQI in this well was obtained. R35 was plotted against RQI in fig. 1 to find an equation in terms of RQI:

$$R35=12.885RQI^{-1.178} \qquad \text{Eq. 2}$$

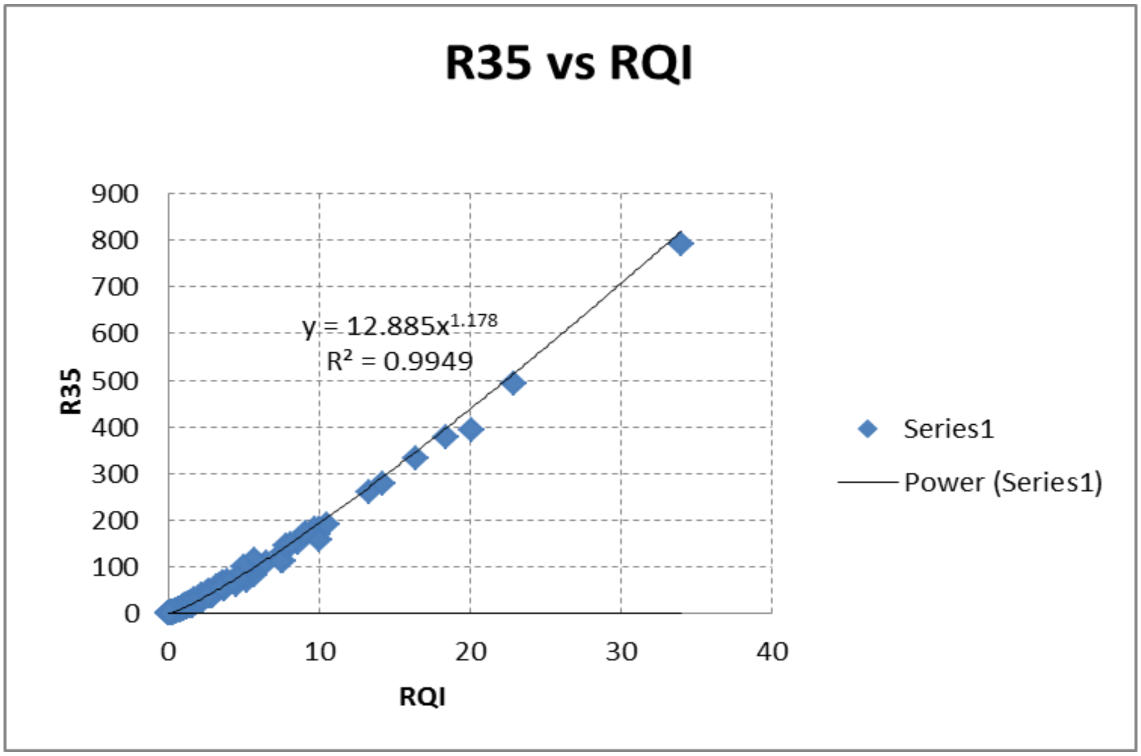


Figure 2: R35 versus RQI

Equation 2 was multiplied by a factor (1.35) to calculate the entry pore throat radius (Equation 3). The factor, 1.35, was determined based on studies of other carbonate reservoirs.

$$R_{entry}=1.39 * (a * RQI^{b}) \qquad \text{Eq. 3}$$

Entry pressure was calculated using Equation 3 and interfacial tension between CO_2 and brine, Equation 4:

$$P_e=\frac{2*\sigma cos\theta*0.147}{1.39*(a*RQI^{b})} \qquad \text{Eq. 4}$$

A function between entry pressure and RQI was found by calculating Equation 4 for P_{entry} in terms of RQI. Interfacial tension of 30 dyne/cm was calculated using an equation from an article, "***Interfacial Tension Data and Correlations of Brine/CO_2 Systems under Reservoir Conditions, (Chalbaud et al. 2006).***" A contact angle of zero was used for the CO_2-brine system. After simplifying, Equation 4 becomes:

$$P_e=0.49*RQI^{-1.178} \qquad \text{Eq.5}$$

b. Irreducible Water Saturation

Irreducible water saturation is needed to calculate normalized non-wetting phase saturation (SnWn). Based on irreducible water saturation of SCAL data, mainly carbonate reservoirs, irreducible water saturation at certain capillary pressure can be correlated very well to the RQI of the rock. There is a good correlation between irreducible water saturation of reservoir rocks and RQI. NMR data of Well 1-32 were used to determine irreducible water saturation at a Pc of 20 bars (290 psi). Also interfacial tension between CO_2 and water was given to the Tech-Log Module to find Swir versus depth for this well. Irreducible water saturation in Well 1-32 in the Arbuckle is plotted against RQI in fig. 3.

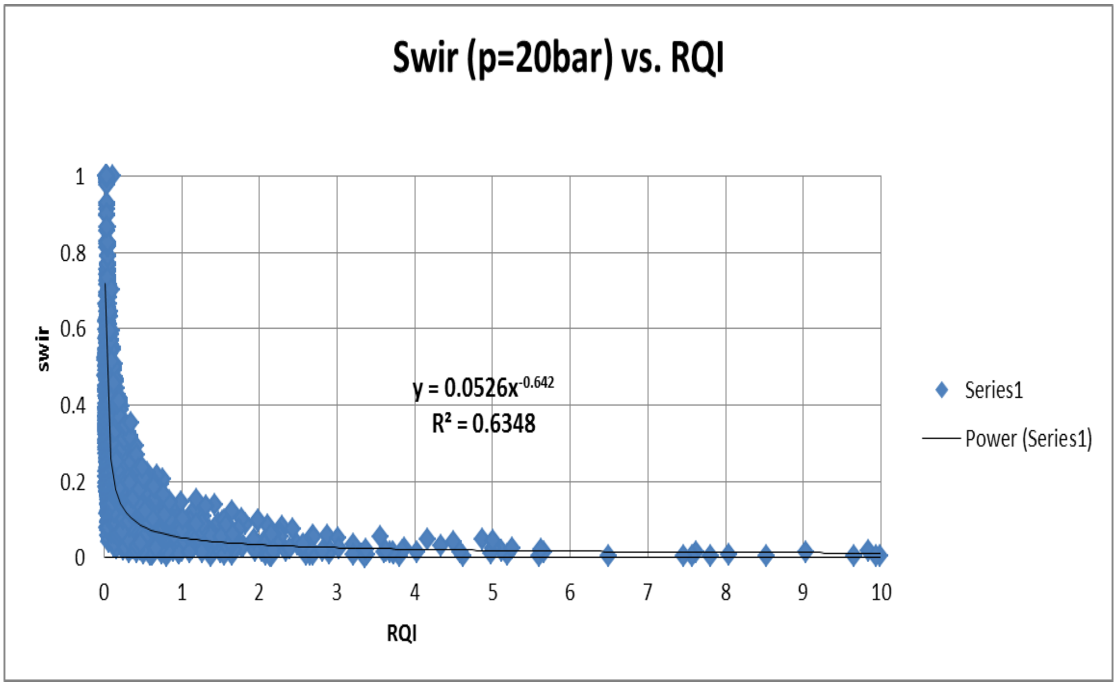


Figure 3: Irreducible water saturation vs. RQI

The relation between swir and RQI was obtainedfrom Figure 3, Eq. 6::

$$Swir=0.0526*RQI^{-0.642} \quad \text{Eq. 6}$$

c. Shape of Normalized Pc curve

The Pc curves that were obtained from NMR (fig. 1) were normalized by plotting SnWn (Normalized Non-Wetting Phase Saturation, Equation 9) versus EQR (Equivalent Radius, Equation 7). The shape of normalized Pc curves appears in fig 4. To find EQR at any Pc, entry pressure of the Pc curve was used. A function in the form of Equation 7 was fit through the normalized data points in fig. 4 and constants a and b of this equation were found.

$$S_{nwn} = (1 - aEQR)(1 - EQR^{b})$$ Eq. 7

*a =1*10^-6*

b=0.898

Equivalent radius is a function of entry pressure and capillary pressure (Equation 8), where entry pressure is a function of RQI, which is given by Equation 5.

$$EQR = \frac{P_e}{P_c}$$ Eq. 8

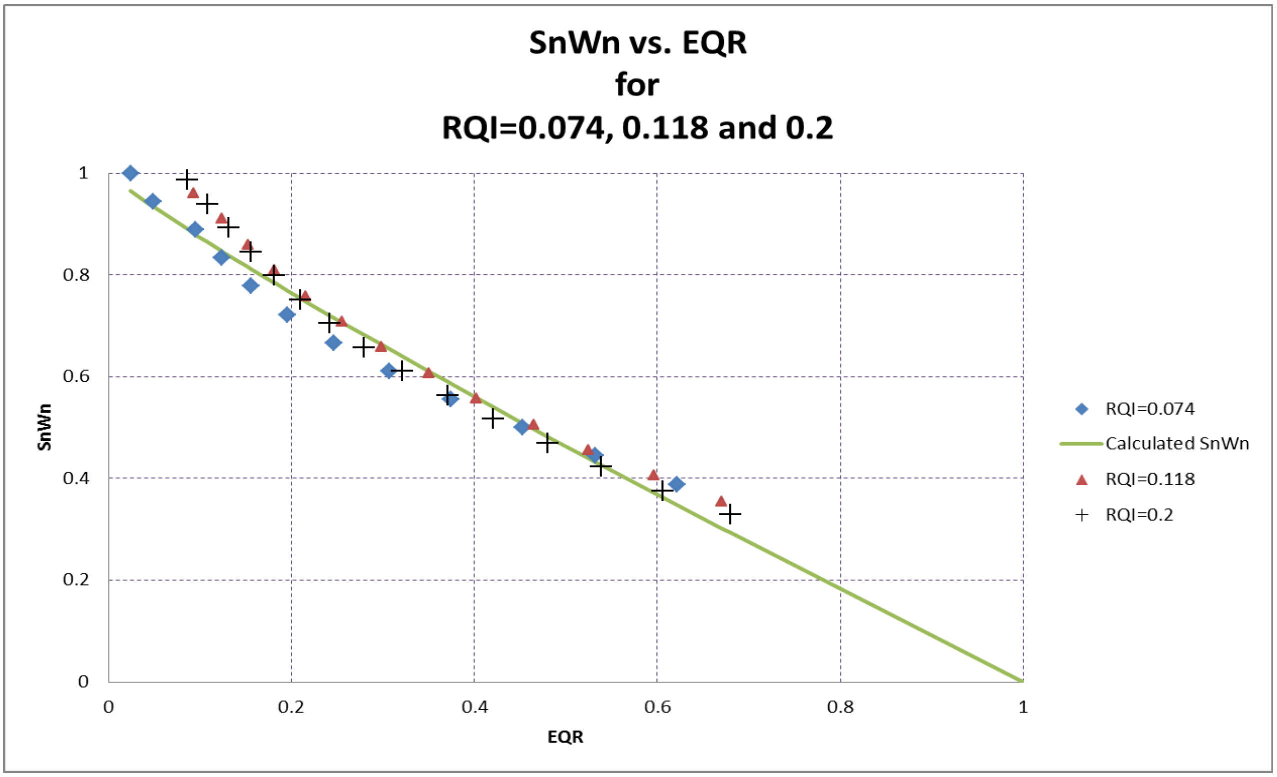


Figure 4: SnWn vs. EQI for RQI 1, 5.19 and 20

Equation 9 defines SnWn (normalized non-wetting phase saturation). Irreducible water saturation was calculated using equation 6 and initial water saturation is known at every Pc.

$$S_{nwn} = \frac{1 - S_{wi}}{1 - S_{wir}}$$ Eq. 9

Values of constants a and b of Equation 7, which were derived by regression before, were replaced in Equation 7 to get Equation 10. This equation will be used to calculate drainage capillary pressure curves.

$$S_{nwn} = (1 - 1 * 10^{\wedge} - 6\frac{P_e}{P_c})(1 - \frac{P_e}{P_c}^{0.898})$$ Eq. 10

d. Calculation of Drainage Capillary Pressure Curves

Equation 11 is obtained from Equation 9 and will be used for calculating drainage water saturation:

$$S_{wi} = 1 - S_{nwn}(1 - S_{wir}) \qquad \text{Eq. 11}$$

According to Equation 11, initial water saturation (Swi) is a function of Snwn . It was shown that Snwn is a function of Pe and Pc (Equation 10), where Pe is a function of RQI. Snwn in Equation 11 can be replaced by respective functions and an equation can be obtained that expresses Swi in terms of RQI and Pc:

$$S_{wi} = 1 - \left(1 - a\frac{0.507RQI^{-1.178}}{P_c}\right)\left(1 - \left(\frac{0.507RQI^{-1.178}}{P_c}\right)^b\right)(1 - 0.0526RQI^{-0.642}) \qquad \text{Eq.12}$$

Constants (a and b) were previously found (Equation 7). They were incorporated into Equation 12, which gives water saturation for every Pc and RQI. Nine Pc curves were calculated for nine rock types. RQI in the Arbuckle changes from 0.017 to 34. This range was divided into nine subdivisions (table 1):

Table 1: Subdivisions of RQI range

RT	RQI from	RQI To	Ave RQI
1	40	10	25
2	10	2.5	6.25
3	2.5	1	1.75
4	1	0.5	0.75
5	0.5	0.4	0.45
6	0.4	0.3	0.35
7	0.3	0.2	0.25
8	0.2	0.1	0.15
9	0.1	0.01	0.055

The mid-range of each subdivision was used to calculate 9 Pc curves using Equation 12, Table 2. The generated Pc curves are shown in fig. 5. These curves are in agreement with NMR Pc curves, when the right permeability and RQI are considered and compared (fig. 6).

Nomenclature

a= constant
b= constant
EQR = Equivalent Radius
NMR= Nuclear magnetic resonance
P_e = Entry Pressure
PC=capillary pressure
RQI= Reservoir Quality Index (μm)
R35= Winland R35
R_{entry}= pore throat radius at entry pressure
Snwn = Normalized non-wetting phase saturation
Swi =Initial water saturation
S_{wir}= Irreducible water saturation (fractional pore volume)

Table 2: Nine Pc curves for nine RQI

a 0.000001	b 0.89773	Drainage PcTable in Arbuckle							
RQI	25	6.25	1.75	0.75	0.45	0.35	0.25	0.15	0.055
Pe	0.011107	0.056862	0.254725	0.691113	1.261498	1.696129	2.521144	4.601882	15.00457548
swir	0.006661	0.016219	0.036724	0.06327	0.087826	0.103203	0.128088	0.177801	0.338589041
Pc	swi								
0	1	1	1	1	1	1	1	1	1
0.1	0.145	0.609	1	1	1	1	1	1	1
0.2	0.081	0.334	1	1	1	1	1	1	1
0.3	0.058	0.237	0.868	1	1	1	1	1	1
0.4	0.046	0.187	0.679	1	1	1	1	1	1
0.5	0.039	0.156	0.563	1	1	1	1	1	1
0.6	0.034	0.135	0.483	1.000	1	1	1	1	1
0.7	0.031	0.120	0.425	0.989	1	1	1	1	1
0.8	0.028	0.108	0.382	0.885	1	1	1	1	1
0.9	0.026	0.099	0.347	0.802	1	1	1	1	1
1	0.024	0.091	0.319	0.736	1	1	1	1	1
2	0.016	0.056	0.188	0.424	0.691	0.877	1	1	1
3	0.013	0.044	0.142	0.314	0.507	0.641	0.874	1	1
4	0.012	0.038	0.118	0.257	0.412	0.518	0.704	1.000	1
5	0.011	0.034	0.103	0.222	0.353	0.443	0.600	0.941	1
6	0.010	0.031	0.093	0.198	0.313	0.392	0.528	0.826	1
7	0.010	0.029	0.086	0.180	0.284	0.354	0.477	0.742	1
8	0.009	0.028	0.080	0.167	0.262	0.326	0.437	0.678	1
9	0.009	0.027	0.076	0.157	0.244	0.304	0.406	0.628	1
10	0.009	0.026	0.072	0.148	0.230	0.286	0.381	0.587	1
12	0.009	0.024	0.067	0.136	0.209	0.258	0.343	0.526	1
14	0.008	0.023	0.063	0.126	0.193	0.238	0.315	0.481	1.00
20	0.008	0.021	0.056	0.109	0.164	0.201	0.264	0.398	0.850
30	0.007	0.020	0.050	0.095	0.141	0.171	0.222	0.331	0.694
40	0.007	0.019	0.047	0.088	0.129	0.156	0.201	0.296	0.613
50	0.007	0.018	0.045	0.083	0.121	0.146	0.188	0.274	0.563
60	0.007	0.018	0.044	0.080	0.116	0.140	0.179	0.260	0.529
70	0.007	0.018	0.043	0.078	0.113	0.135	0.172	0.249	0.505
80	0.007	0.018	0.042	0.076	0.110	0.131	0.167	0.241	0.486
90	0.007	0.018	0.042	0.075	0.108	0.129	0.163	0.235	0.471
100	0.007	0.017	0.041	0.074	0.106	0.126	0.160	0.230	0.459
150	0.007	0.017	0.040	0.071	0.100	0.119	0.150	0.214	0.422
200	0.007	0.017	0.039	0.069	0.097	0.116	0.145	0.206	0.403
300	0.007	0.017	0.038	0.067	0.095	0.112	0.140	0.197	0.384

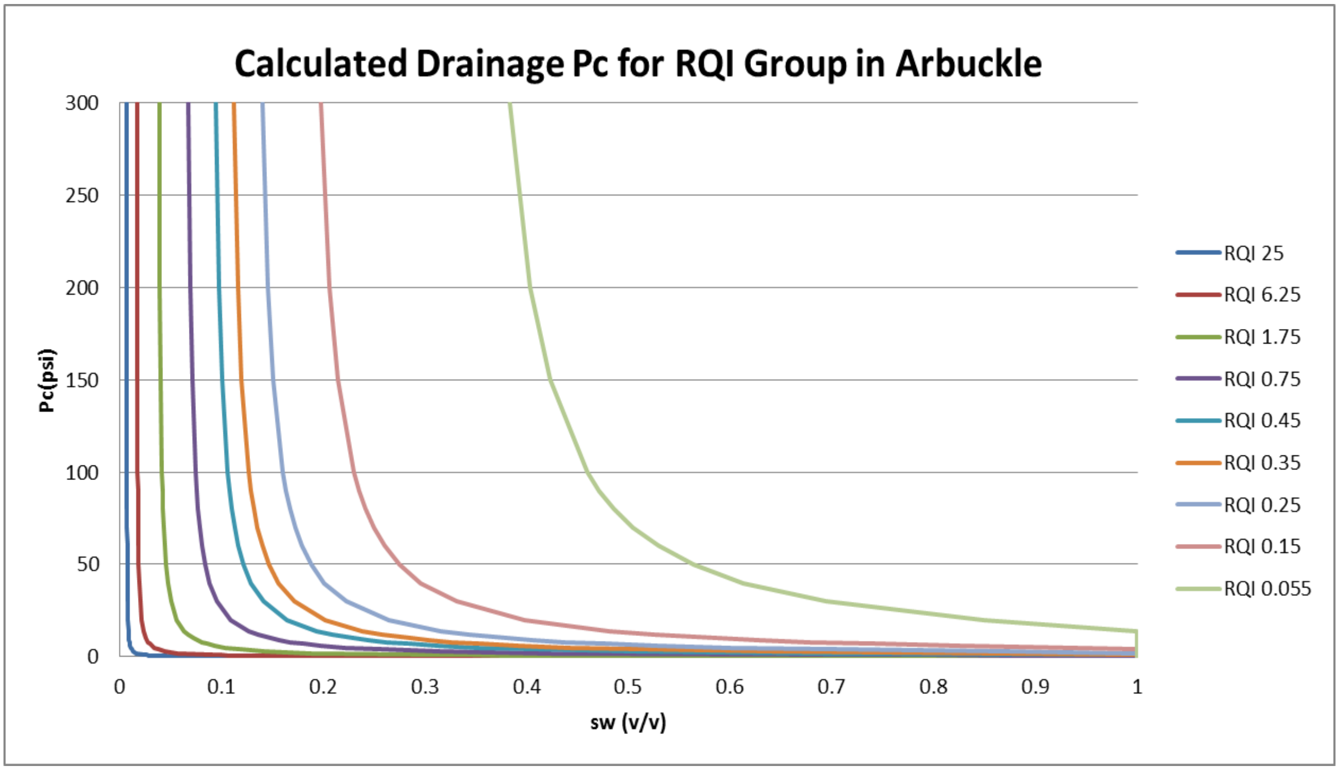


Figure 5: Nine Pc curves for nine rock types for the specified RQI

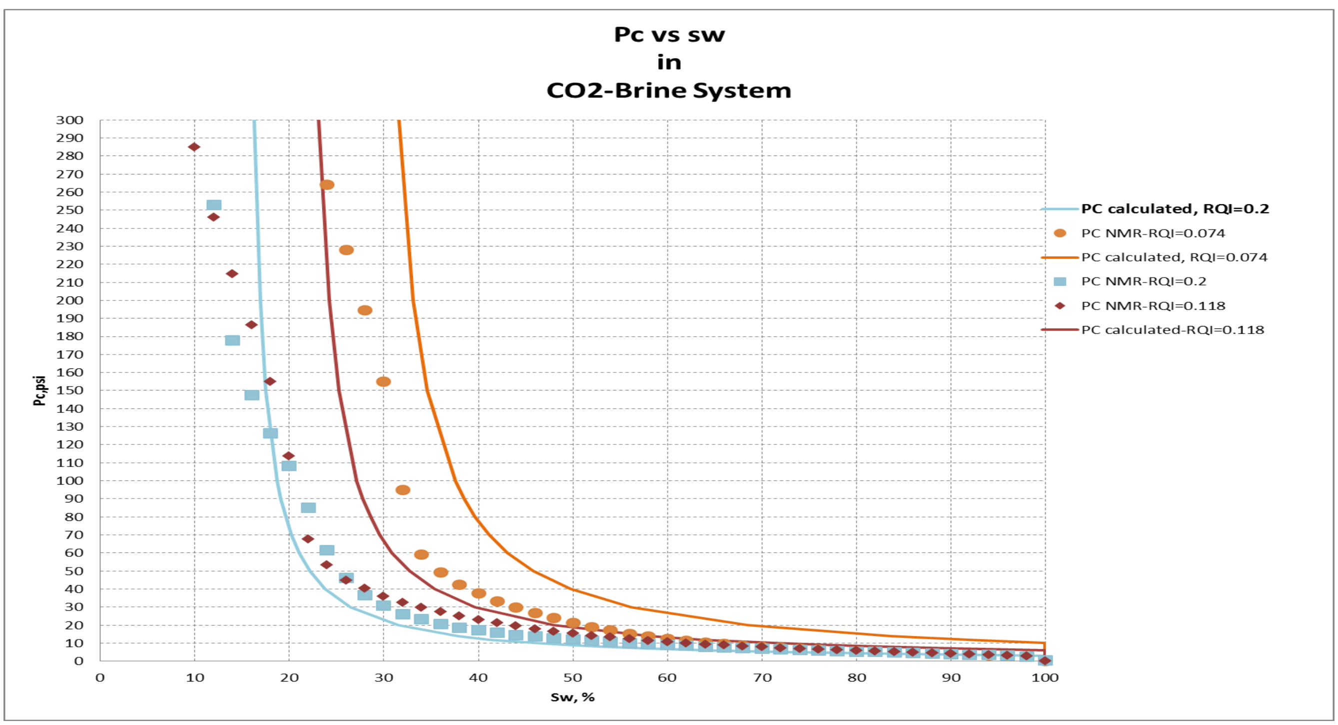
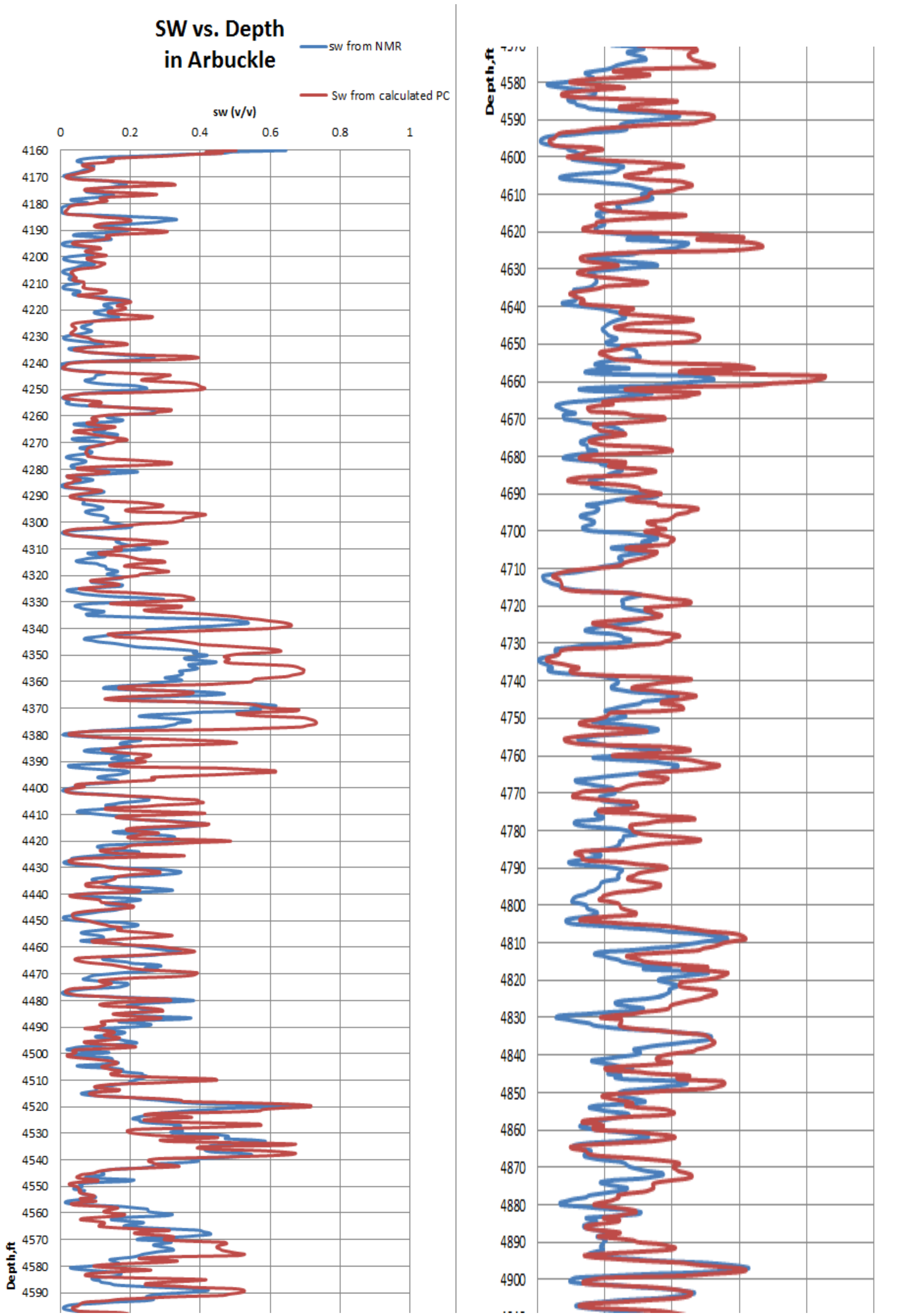


Figure 6: Calculated Pc compared with generated Pc from NMR


SW vs. Depth
in Arbuckle
sw from NMR
Sw from calculated PC
sw (v/v)
0
0.2
0.4
0.6
0.8
1
Depth,ft
4160
4170
4180
4190
4200
4210
4220
4230
4240
4250
4260
4270
4280
4290
4300
4310
4320
4330
4340
4350
4360
4370
4380
4390
4400
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4500
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4530
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4550
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4570
4580
4590
Depth,ft
4580
4590
4600
4610
4620
4630
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4690
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